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Auditory Localization Performance with Gamma Integrated Eye and Ear Protection

by Angelique Scharine, Morgan Domanico, Ashley Foots, Timothy Mermagen, and Rachel Weatherless

NOTICES

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Auditory Localization Performance with Gamma Integrated Eye and Ear Protection

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14. ABSTRACT

Auditory localization performance was assessed for participants wearing the gamma integrated eye and ear protection (IEEP), a prototype tactical communications and protection system that also provides eye protection. Testing was conducted using one of the auditory localization measurement methods recently proposed as a standard by the Department of Defense Hearing Center of Excellence. Participants used a laser pointer to indicate the perceived location of a sound presented from 1 of 36 loudspeakers. This task was completed both with ears unoccluded (no IEEP) and with the IEEP. Pink noise was used for the sound stimuli (either 250 ms or 4000 ms), randomly roved from 60 to 75 dBA. Localization accuracy was measured as the horizontal angular difference between the target loudspeaker location and the participant's estimate. The data were analyzed taking into account individual ability, as well as the known effects of sound source azimuth and stimulus duration. After taking these known effects into account, we concluded the IEEP did not significantly change overall localization ability. However, it did have a small, but significant, effect on accuracy for the short-duration (250 ms) stimuli due to an increase in reversals (front-back confusions).

15. SUBJECT TERMS

auditory localization, TCAPS, hearing protection, eye protection, auditory situation awareness

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1.   Introduction

This effort was funded by the US Army Natick Soldier Research, Development and Engineering Center's (NSRDEC's) Warfighter Directorate. The objective was to measure the effect of a prototype designed to provide Soldiers with integrated eye and ear protection on auditory localization ability.

1.1 Gamma Integrated Eye and Ear Protection (IEEP)

The IEEP (Fig. 1) was manufactured for NSRDEC by Applied Research Associates, Inc. (ARA) and Revision Military Technologies under contract W911Q7-13-C0099. The Gamma-IEEP combines ARA's hybrid hearing protection technology with Revision Military's Sawfly Military Eyewear System. According to the manufacturer, in addition to ballistic eye protection and distortion free vision, the hearing protection portion of this technology provides passive sound attenuation capabilities and electronic limiters that suppress transmission of impulsive and high-level steady-state noise. In addition, the manufacturer indicates that the system's active pass-through microphone technology restores normal levels of hearing when ambient noise levels are below 85 dBA.[*] Testing was conducted with the system active.

Fig. 1   IEEP device under test: shown with clear ballistic lens and Comply foam earphone tips.

1.2 Auditory Localization

Localization of a sound source is determined using binaural, monaural, and movement-based cues. Binaural cues are the result of differences in arrival time and sound pressure level between the 2 ears, providing information about the right/left position of a sound. Monaural cues are created as the sound reflects off parts of the body and these reflections add into the original sound wave. Monaural cues give information about a sound's elevation and placement along the front-back

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[*] Decibels A-weighted" is the sound pressure level adjusted for the sensitivity of the average human ear. The reference level is the loudness of a 1000-Hz tone presented at 40-dB sound pressure level. Humans are less sensitive to low frequencies and more sensitive to frequencies between 1 kHz and 10 kHz.

axis. Movement of the head provides multiple sets of binaural cues, which in combination with information about the head's movement reduces ambiguity in these binaural cues and increase accuracy of localization estimates.

Auditory localization errors stem from failure to fully resolve binaural and monaural cues. Imprecision with respect to binaural cues are the source of localization blur. Localization errors due to limitations in acuity are called localization blur, and this underlying variability is due to our limited ability to resolve binaural information. Humans can localize horizontally only within a certain range of error. Localization capability is further limited by the ability to discriminate between 2 sound sources: the minimum discriminable audible angle (MAA). In studies of the MAA, normal hearing listeners can, on average, reliably discriminate audible angles that differ by only $0.97°$ at $0°.$[*] However, this discriminability decreases to $3.65°$ at $90°$ (Saberi and Perrott 1990). This ability to discriminate between 2 source locations is thus reflected in measures of ability to localize a single sound source. If the response options are limited to the front hemisphere, measures of localization acuity range from approximately $4°$ at the midline ($0°$) to $9°$ at the interaural axis ($90°$) (Oldfield and Parker 1984).

The auditory spatial cues provided by brief transient sounds are vulnerable to distortion and masking. Binaural cues only specify a ring of potential locations known as the cone of confusion (Fig. 2), all sharing the same interaural time and intensity differences. Monaural cues can be used to resolve this ambiguity but they require that the listener have some prior knowledge of the sound source. The spectral changes that are the source of monaural cues can be altered by changes in hairstyle and the head's profile, as well as masked by reflections and reverberation. In practice, these ambiguities are often resolved by movements of the head and visual confirmation (Wallach 1940).

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[*] For the sake of discussion, 0° refers to directly in front of the listener. 90° refers to the angle directly to the right of the listener.
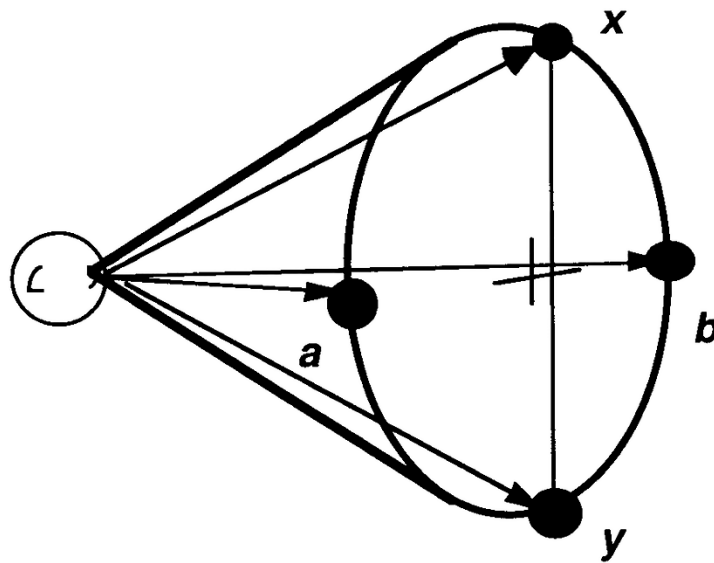
Fig. 2 Schematic representation of the "cone of confusion," described as the set of locations sharing the same set of binaural difference cues

Movement is often ignored in laboratory studies of localization; however, in more ecologically relevant conditions, it is a predominant cue. For longer sounds, head movements can provide the listener with multiple "samples" of auditory spatial information, greatly reducing the ambiguity (Wallach 1940). To make studies of auditory localization sensitive to other factors that affect localization, the sound signals are often kept brief in duration to prevent the listener from using movement cues, thus increasing the probability of errors due to altered monaural cues. Because the listener in these studies typically cannot use movement cues, data from these studies can be interpreted to represent the lower limit of localization ability. Given a longer stimulus duration, additional information is available in binaural, monaural, and movement cues that the listener can use to localize the sound source (Thurlow et al. 1967). Therefore, testing with longer stimuli provides information about the upper boundary of individual localization ability.

When movement cues are absent, monaural cues are required to resolve binaural ambiguity. Failure to resolve this ambiguity manifests itself in errors that result from choosing another location within the cone of confusion that has similar binaural information, but different monaural information. Thus, if the potential response set is limited to the horizontal axis, the error for location "a" in Fig. 2 results in choosing location "b" that is located in the same right/left position, but mirrored about the interaural axis in the reverse hemisphere.

1.3 Localization with Hearing Protection and Other Headgear

Hearing protection devices (HPDs), tactical communications and protection systems (TCAPS), and other forms of headgear have been shown to alter the perception of monaural cues, resulting in both increased localization blur and front-back confusions. For example, physical changes to the region around the ears alter the monaural information in the head-related transfer function of the sound path and negatively affect the auditory localization performance of the listener (Riederer 2003a, 2003b). Previous research has shown that helmets can increase unsigned localization errors on average as much as 13° (Scharine et al. 2014). Scharine and Weatherless (2014) measured increases to average unsigned localization error of approximately 18° for passive, level-dependent earplug style HPDs. Similar increases were measured for active earplug (~20°) and earmuff (~25°) style TCAPS (Scharine and Weatherless 2013). In both cases, increases in front-back confusions near 0° and 180° were observed. These well-documented effects have led to the inclusion of auditory localization ability as a measure of auditory "situation awareness" for TCAPS, and it has been included as an element of the requirements drafted during the acquisition of Soldier equipment.

1.4 Standardization of Localization Measurement

Recently there has been an effort to establish standard measurement methods for the assessment of hearing protection offered for use by the Department of Defense (DOD). In April of 2016, a DOD Hearing Center of Excellence (HCoE) working group meeting was held at Wright Patterson Air Force Base to discuss implementation of a uniform methodology for measurement of localization ability (Buchanan 2016). Three methods were proposed, 2 that measure auditory localization, and a third that measures audio-visual target detection. Apart from a few minor details that will be described further, the IEEP was tested according to the proposed Method 2 described in the following sections.

1.5 Auditory Localization Measurement Methods 1 and 2

1.5.1 Loudspeaker Array

Method 1 was developed as a simple and cost-effective measurement approach for manufacturers and others who do not have access to controlled acoustic facilities with large loudspeaker arrays. Method 1 has 2 listener orientations (0° and 45°) and specifies the use of 8 loudspeakers, strategically placed to allow the experimenter to detect differences in auditory localization blur and front-back localization errors.

In contrast, Method 2 was developed for those who wish to more fully characterize the auditory spatial performance of listeners, either for research purposes or after down-selecting items tested with Method 1. Method 2 requires a hemi-anechoic facility, a horizontal array of 24–36 evenly spaced loudspeakers, and a position tracker that allows the listener to respond to the full 360° horizontal range.

1.5.2 Stimulus Duration

Real-world environments contain sounds of varying durations. Both methods specify the use of 2 different stimulus durations: short (250 ms) and long (4000 ms).[*] The effects of stimulus duration on auditory localization have been established in research (Vliegen and Van Opstal 2004; Bernhard 2015). The short sound is used to prevent participants from turning their head to use movement cues to disambiguate the binaural information. The long sound provides time for the participants to move their head and gather more information that disambiguates the binaural information, providing an estimate of upper limit of the participants' localization accuracy. Performance, as measured for the short and long stimuli, characterizes the range of localization ability demonstrated in the real world. To obtain reliable measurements in the minimum testing time, twice as many short stimuli are presented as long stimuli. More trials are needed for the short-duration stimuli due to greater variability in localization for these stimuli. In contrast, fewer presentations are required for the long-duration stimuli, as listeners are able to be both quite consistent and accurate.

Currently no criteria exist for auditory localization performance with TCAPS; however, measures of auditory localization performance for a similar TCAPS device showed an average increase in error of approximately 25° for short-duration stimuli (Scharine and Weatherless 2013). It is likely that TCAPS more greatly impairs the localization of short stimuli because listeners are forced to rely only on monaural cues for their localization estimates. To the extent which the TCAPS preserves binaural information, they are predicted to minimally affect localization of long-duration stimuli since the user can gather more information through head movement. The IEEP is similar to other TCAPS devices in that there are small earphone tips used to provide passive protection from noise, as well as to transmit radio and ambient communications. Further, the protective lenses may reflect and

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[*] The method proposed actually specifies that the longer stimuli should be at least 1000 ms, up to 7000 ms. The stimulus is supposed to play until the listener responds. The testing apparatus did not permit us to stop the stimulus once triggered. Therefore, a workaround was to present a shorter stimulus of 4000 ms that was sufficiently long enough to allow the listener to respond, but not so long as to have them sitting and waiting for it to end.

alter auditory information. Therefore, the IEEP should reduce localization ability. The objective of this study was to characterize these effects.
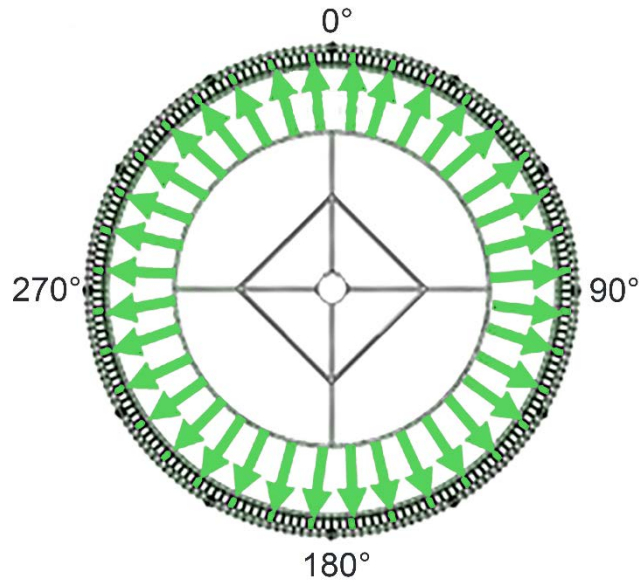
2. Method

2.1 Participants

Six participants participated in the testing. Study criteria required that they be age 18 or older and have normal hearing. Normal hearing was defined as bilateral hearing thresholds no greater than 25 dB HL* at all audiometric frequencies from 250 Hz to 8 kHz, including 3 kHz and 6 kHz. Further, bilateral threshold differences were not greater than 15 dB at a given frequency. Prior to testing, participants' ear canals were visually inspected with an otoscope to ensure normal morphology and the absence of earwax and debris that might prevent the insertion of earphone tips.

2.2 Test Facility

The study was conducted in the Dome Room of the Environment for Auditory Research, a large sound-treated room instrumented with a horizontal array of 180 loudspeakers positioned at 2° increments (Henry et al. 2009). Thirty-six of the 180 loudspeakers were used for Method 2; the participant was oriented so that the loudspeakers start at 5°, and there are 36 loudspeakers at 10° increments from 5° to 355° (Fig. 3). The loudspeakers were marked during training by placing a pink ping-pong ball in a divot centered on the top of the loudspeaker. Participants were not provided with feedback during training or testing, so these markers were used to teach the listeners where the potential source locations would be and to increase the probability of reliable performance during training. During testing, these markers were removed to reduce the interaction of visual information with auditory spatial cues.

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*Decibels hearing level (dB HL) is the sound pressure level, in decibels, relative to the average human threshold level.

0°

270°   90°

180°

Method 2

Fig. 3   Loudspeaker configuration in the dome room: method 2 testing incorporates 36 loudspeakers spaced at even intervals of 10°, beginning at 5° and continuing to 355°

All sound presentation was controlled using a custom MATLAB R2014b (Mathworks 2014) script running on a computer operating Windows 7 and located in a separate control room. Research participants were seated in a rotating chair instrumented with a tracking system. Participants responded by rotating the chair and pointing a laser pointer at the perceived source location. The tracking system's response coordinates were recorded by the control room computer.

2.3 Localization Test

2.3.1 Target Stimuli

The target stimulus was a randomly generated pink broadband (200 Hz–14 kHz) noise signal, edited to 1 of 2 stimulus durations, short (250 ms) and long (4000 ms) with 10-ms cosine onset and offset ramps. To avoid the use of stimulus level as a source of localization information, stimulus level was randomly varied to 1 of 4 levels (60, 65, 70, and 75 dBA).

2.3.2 IEEP Earphone Tip Fitting

A Comply Canal Tips Fitting Guide[*] measurement tool was used to identify the proper sized earphone tips for each participant. Participants were then instructed on proper insertion of the earphone tips and asked to practice inserting them until they felt comfortable doing so. The experimenter verified that the earphone tips were placed so as to be fully inserted in the ear canal, but did not assist with insertion after training.

2.3.3 Stimulus Blocks

Training: A block of trials consisted of 3 trials (1 long- and 2 short-duration signals) presented from each of 10 test locations for a total of 30 trials, randomly selected for each participant from the locations to be used in the test. The order of trials (duration and location) was random. Participants trained on the training blocks for at least 5 blocks. After the fifth block, if the average error for the last block was within ± 30% of the mean error for the last 5 blocks and no greater than 15°, the participant moved on to testing. If not, training continued until the criteria were met. All training was completed without the IEEP. All participants tested were able to meet the training criteria in fewer than 8 training blocks.

Testing: A block of trials consisted of 3 trials (1 long- and 2 short-duration signals) from each of the 36 locations. Each block, therefore, had 72 short and 36 long trials. Participants completed a total of 8 blocks of trials, 4 blocks with the ears unoccluded (no IEEP) followed by 4 blocks with the IEEP. During the last 4 blocks, the IEEP was refitted after 2 blocks.

3. Results

3.1 Independent Variables

The design of the experiment was a 4-factor, within-subjects design. The 4 independent variables included in our analyses were IEEP use, stimulus duration, stimulus level, and sound source azimuth. The independent variable of primary interest was the effect of IEEP usage on localization error. However, a number of other factors were included in the analyses due to the known effects on error or to ensure that an irrelevant factor did not impact localization accuracy. Localization accuracy is known to vary as a function of sound source azimuth (horizontal location of sound source) and stimulus duration and therefore these factors were included in the analyses. Stimulus level was a random variable, and was not

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[*]Comply canal tips are manufactured by SELEX communications.

expected to affect localization ability as long as the target signal was sufficiently audible allowing participants the use of spatial information within the signal. It was included in the analyses to verify that that there are no differences in performance due to failure to hear the target signal.

3.2 Dependent Variables

Horizontal localization error was measured as both the signed and unsigned angular difference between the source location and the location of the loudspeaker nearest the response location. Localization performance with the IEEP was compared to performance with the ears unoccluded (no IEEP).

3.3 Individual Differences

Individual localization ability differed significantly across the participants. Figure 4 shows the unsigned error (magnitude) for each participant as a function of IEEP use and stimulus duration. Note that there appears to have been a malfunction with the IEEP during the fourth subject's testing. Because performance was clearly outside the range of performance found for the other participants, these data were dropped from the analyses.[*]
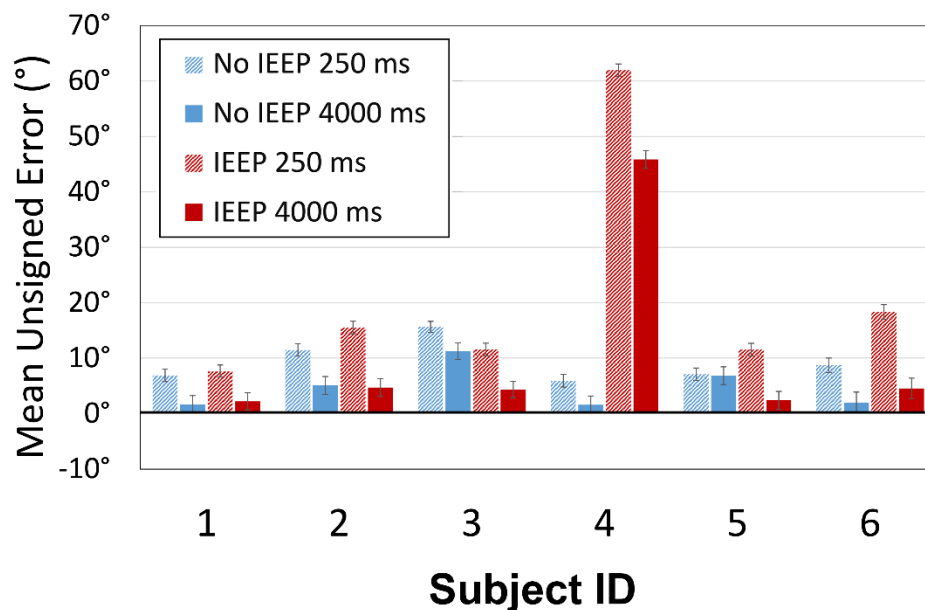

Fig. 4   Mean unsigned error for each participant, shown as a function of IEEP use and stimulus duration. (Error bars shown are the standard error of the mean)

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[*] Unfortunately, new equipment was installed in the laboratory, making it impossible to retest this participant.

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3.4 Signed Errors

Signed error gives an estimate of bias if it exists in the data. Front-back reversals will become evident by positive errors in the front or negative errors in the back. Listeners can sometimes show a shift toward the interaural or the mid-sagittal axes. Sometimes the acoustics of the research space are asymmetric, or a loudspeaker is not well equalized resulting in asymmetric error patterns. Individuals can also show particular biases, resulting from cognitive or auditory factors. For a detailed discussion see these references (Letowski and Letowski 2012; Scharine et al. 2014). Thus, reporting signed error allows one to assess the strength of the localization data as well as to observe underlying biases. It should be noted that for the relatively small number of participants, perfect symmetry is unlikely.

The experiment was a factorial, within-subjects design. A 4-factor analysis of variance with subjects as a covariate was computed for signed localization error from the 5 participants. Table 1 summarizes the statistical significance of each of the factors.

Table 1   Summary of ANCOVA for signed localization error with subjects as a covariate

Source	df	MS	F	p	partial η^2
Subject	1	652.84	1.98	0.160	0.001
IEEP	1	108.03	0.33	0.567	0.000
Stimulus duration[a]	1	38371.04	116.32	0.001	0.031
Stimulus level	3	335.05	1.02	0.385	0.001
Sound source azimuth[a]	35	1319.70	4.00	0.001	0.037
IEEP × stimulus duration[a]	1	1736.91	5.27	0.022	0.001
IEEP × stimulus level	3	493.51	1.50	0.214	0.001
IEEP × sound source azimuth	35	443.38	1.34	0.085	0.013
Stimulus duration × stimulus level	3	520.25	1.58	0.193	0.001
Stimulus duration × sound source azimuth[a]	35	942.06	2.86	0.001	0.026
Stimulus level × sound source azimuth	105	296.27	0.90	0.761	0.025
IEEP × stimulus duration × stimulus level	3	296.95	0.90	0.440	0.001

Table 1 Summary of ANCOVA for signed localization error with subjects as a covariate (continued)

Source	df	MS	F	p	partial η²
IEEP × stimulus duration × sound source azimuth [a]	35	616.12	1.87	0.001	0.017
IEEP × stimulus level × sound source azimuth	105	221.56	0.67	0.996	0.019
Stimulus duration × stimulus level × sound source azimuth	105	367.83	1.12	0.202	0.031
IEEP × stimulus duration × level × sound source azimuth	105	268.81	0.82	0.915	0.023
Error	3683	329.87	. . .	. . .	. . .

[a] = Significant at α < 0.05 level.

The main effect of stimulus duration was significant, $F(1, 3683) = 116.32$, $p < 0.001$; performance was nearly perfect for the 4000-ms stimuli (Fig. 5). The main effect of sound source azimuth, $F(35, 3683) = 4.00$, $p < 0.001$, reflects a tendency to respond toward the front of the array thus making negative errors (Fig. 6). Both of these effects are consistent with previous auditory localization research (Scharine et al. 2014).
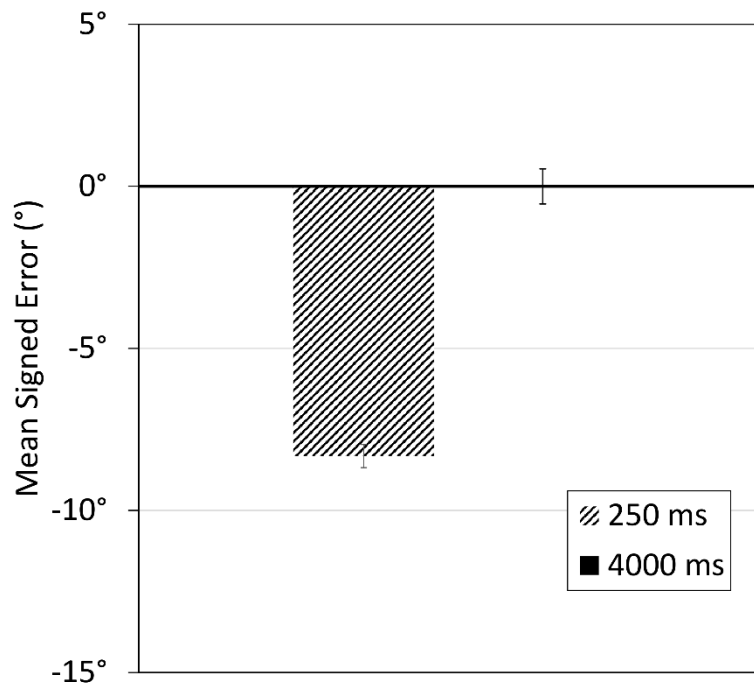

Fig. 5   Signed localization error as a function of stimulus duration
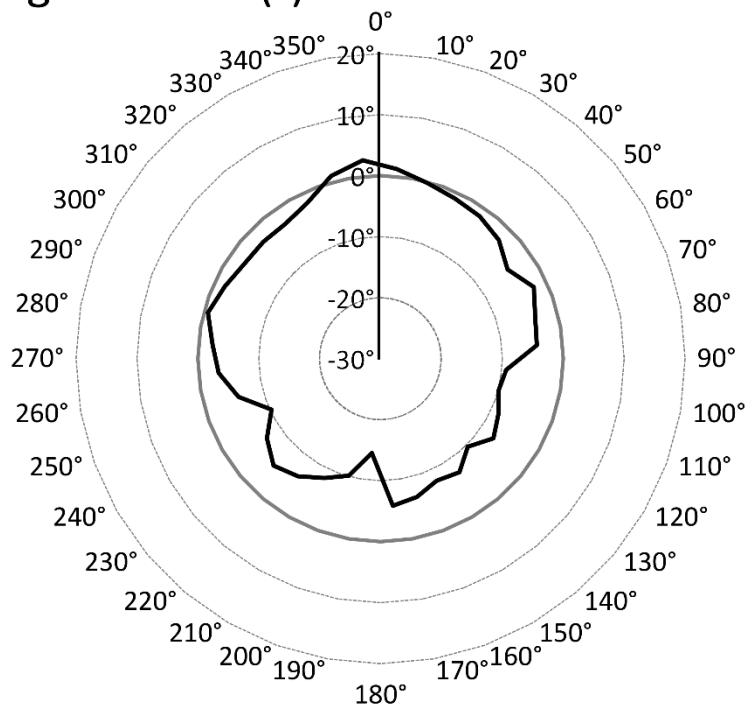
Mean Signed Error (°)

Fig. 6   Overall mean signed localization error shown as a function of sound source azimuth. (The gray circle represents 0° error.)

The interaction of stimulus duration and sound source azimuth is shown in Fig. 7. Errors were very near to zero for the 4000-ms stimuli. In contrast, participants showed a tendency to respond toward the front of the array, resulting in negative error values when presented with the 250-ms stimuli, and this bias increased for sounds originating from the rear hemisphere.
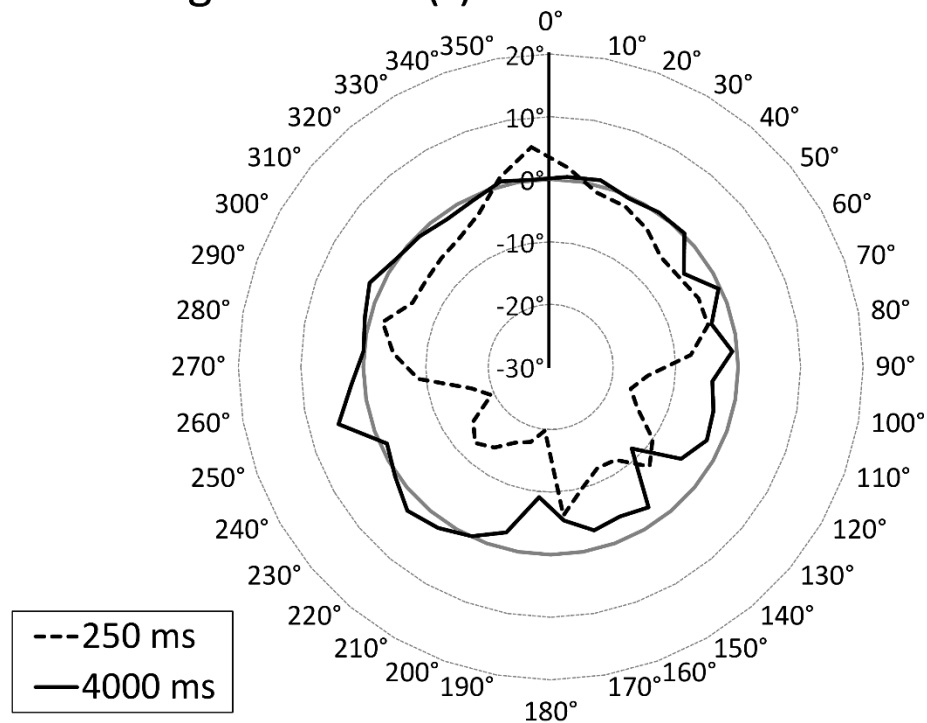
Fig. 7   **Mean signed error as a function of stimulus duration and sound source azimuth**

There was no main effect of IEEP use; however, there was an interaction observed for IEEP use with stimulus duration, $F(1, 3683) = 5.27$, $p < 0.022$. The average signed localization error was –5.9°, suggesting a slight bias to respond to the front of the array. This bias increased an average of 0.8° for the 250-ms stimuli and decreased 1.8° for the 4000-ms stimuli when wearing the IEEP; however, neither simple effect was significant, $p = 0.272$ and $p = 0.074$, respectively (Fig. 8).
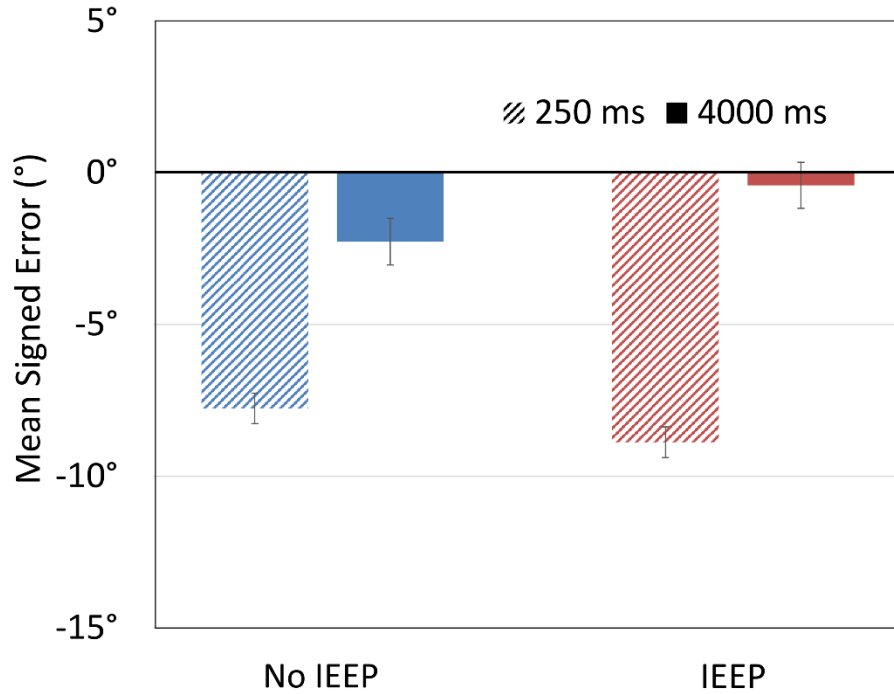
Fig. 8   Mean signed error observed for participants as a function of IEEP use and stimulus duration

The 3-way interaction of IEEP use with stimulus duration and sound source azimuth is shown in Fig. 9, $F(35, 3683) = 1.87$, $p < 0.001$. It should be noted that in many of the previous studies of auditory localization with TCAPS, the target stimulus duration was 250–400 ms (Scharine 2009; Scharine and Letowski 2013; Scharine and Weatherless 2013; Scharine et al. 2014). The effect of IEEP use is more apparent for the 250-ms stimuli and is seen as an increased bias to respond toward the front of the array for stimuli originating from the rear hemisphere, and a smaller bias to respond toward the back for stimuli originating near 0°. Conversely, for the 4000-ms stimuli, there is no significant effect of IEEP use.
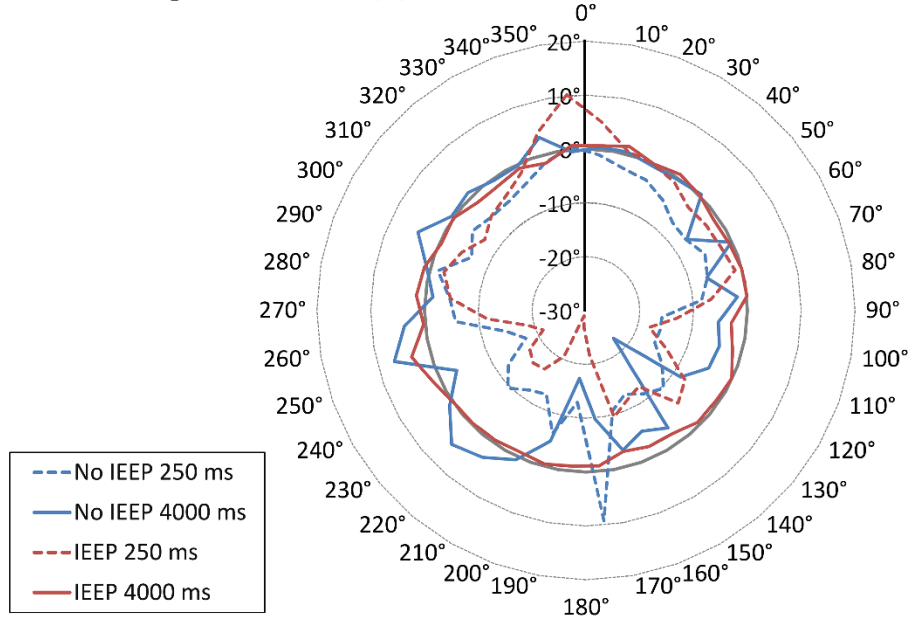
Mean Signed Error (°)

Fig. 9 **Mean signed error as a function of IEEP use, stimulus duration, and sound source azimuth**

3.5 Unsigned Errors

Unsigned error is an estimate of the magnitude of an error. If the errors for individual estimates are large, it is not practically important that the average of those errors be near zero. Good auditory localization performance is that in which average unsigned errors are small. A summary of the 4-factor analysis of variance with subjects as a covariate computed for unsigned localization is given in Table 2.

Table 2 Summary of ANCOVA for unsigned localization error with subjects as a covariate

Source	df	MS	F	p	partial η^2
Subject[a]	1	1641.51	5.53	0.019	0.001
IEEP	1	0.79	0.00	0.959	0.000
Stimulus duration[a]	1	34884.79	117.52	0.001	0.031
Stimulus level	3	67.17	0.23	0.878	0.000
Sound source azimuth[a]	35	1545.31	5.21	0.001	0.047
IEEP × stimulus duration[a]	1	4990.83	16.81	0.001	0.005
IEEP × stimulus level	3	491.60	1.66	0.174	0.001
IEEP × sound source azimuth	35	206.93	0.90	0.909	0.007
Stimulus duration × stimulus level	3	258.15	0.87	0.456	0.001
Stimulus duration × sound source azimuth	35	529.76	1.79	0.003	0.017
Stimulus level × sound source azimuth	105	200.60	0.68	0.995	0.019
IEEP × stimulus duration × stimulus level	3	57.01	0.19	0.902	0.000
IEEP × stimulus duration × sound source azimuth*	35	457.66	1.54	0.022	0.014
IEEP × stimulus level × sound source azimuth	105	180.49	0.61	0.999	0.017
Stimulus duration × stimulus level × sound source azimuth	105	196.20	0.661	0.997	0.018
IEEP × stimulus duration × stimulus level × sound source azimuth	105	214.19	0.72	0.985	0.020
Error	3683	296.84	. . .	. . .	. . .

[a] = Significant at α < 0.05 level.

Figures 10 and 11 show the main effects of stimulus duration, $F(1, 3683) = 117.52$, $p < 0.001$, and sound source azimuth, $F(35, 3683) = 5.21$, $p < 0.001$, respectively. On average, the longer 4000-ms stimulus duration reduced the size of errors by approximately 7°. Error sizes increased by an average of 6° in the rear hemisphere, especially near 180°.
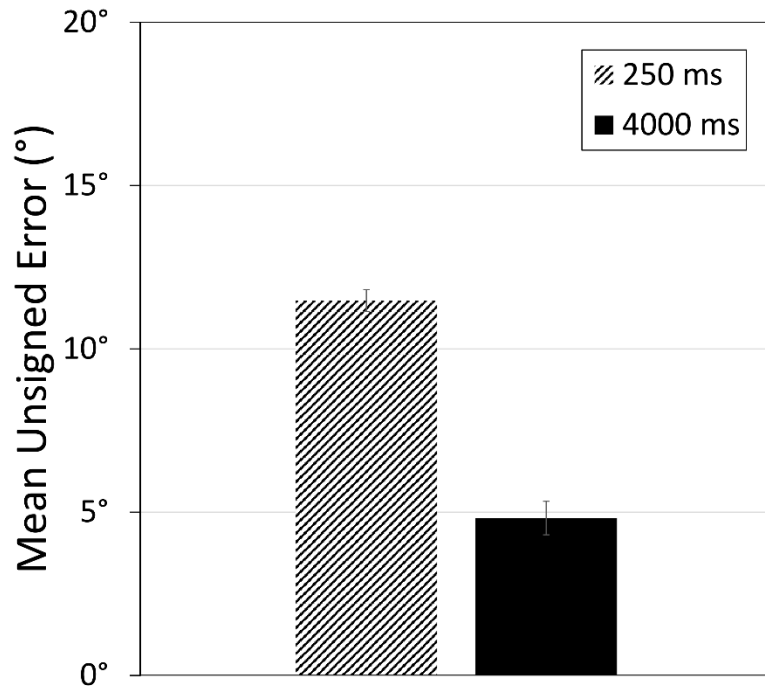

Fig. 10   Mean unsigned error shown as a function of stimulus duration

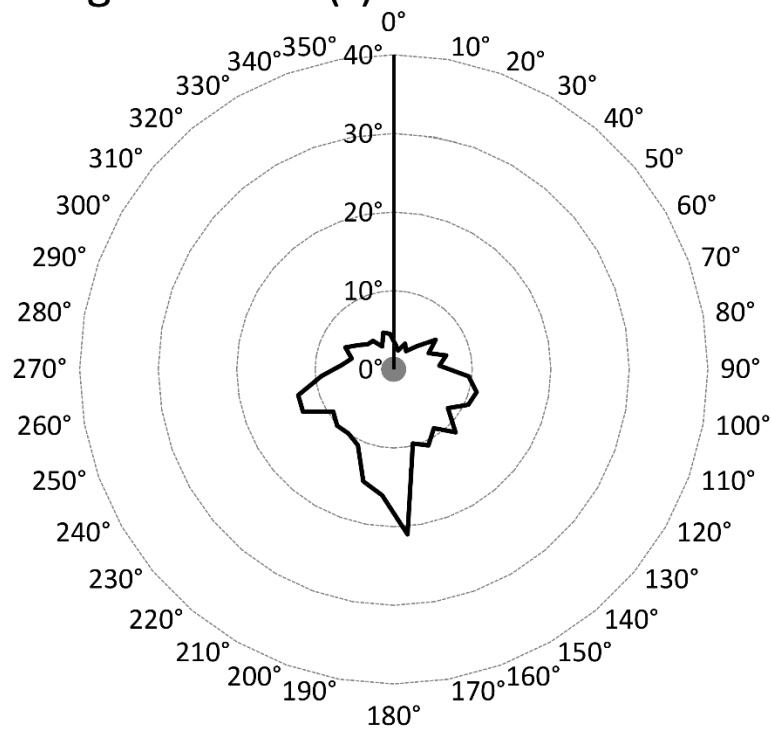## Mean Unsigned Error (°)

Fig. 11   Overall mean unsigned error shown as a function of sound source azimuth

Figure 12 shows the significant interaction of stimulus duration and sound source azimuth, $F(35, 3683) = 2.86$, $p < 0.003$. Overall, errors for the 4000-ms stimuli are very small at most horizontal azimuths. In contrast, there are large errors in the rear hemisphere for the 250-ms stimuli that are probably due to back-front reversals. This will be discussed in the following section.
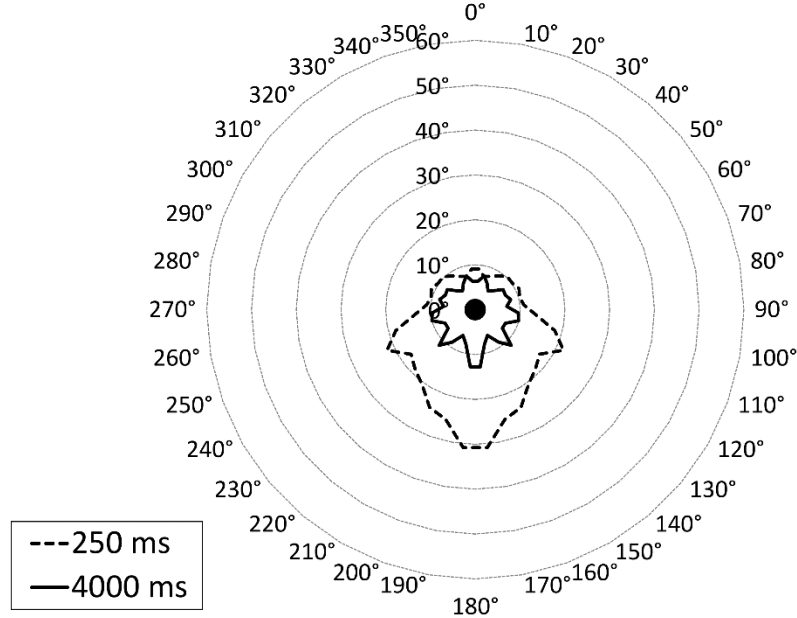
Fig. 12 **Mean unsigned error shown as a function of stimulus duration and sound source azimuth**

As with the signed error, there was no main effect for IEEP use for unsigned error (Fig. 13). There was a 2-way interaction of IEEP use with stimulus duration, $F(1, 3683) = 16.81$, $p < 0.001$. Use of the IEEP increased average unsigned error by 2.2° for the 250-ms stimuli and decreased average unsigned error by 2.2° for the 4000-ms stimuli. A simple effects analysis showed these differences to be significant for both the 250-ms, $F(1, 4259) = 11.00$, $p = 0.001$, and 4000-ms stimuli, $F(1, 4259) = 5.58$, $p = 0.019$.
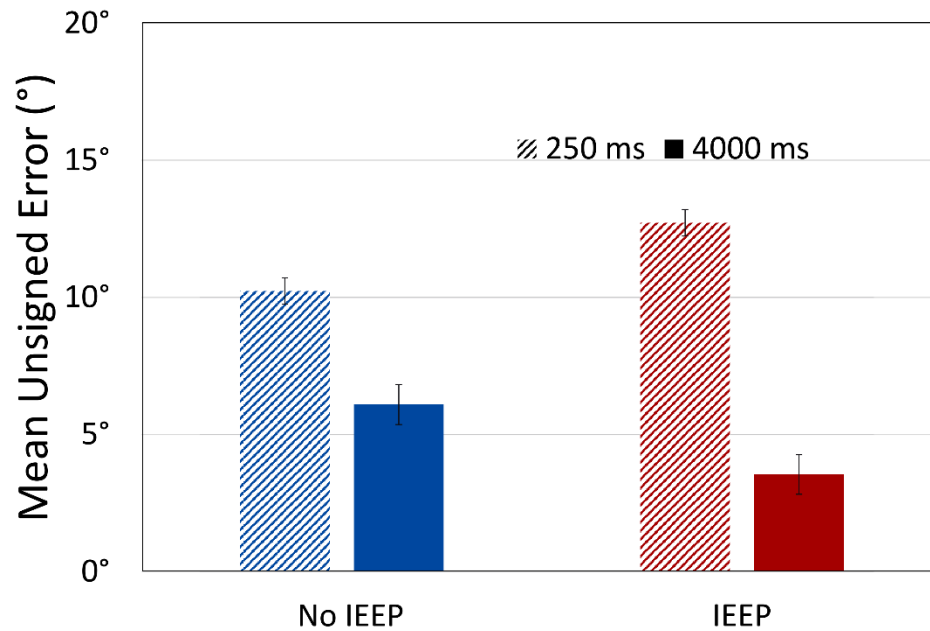
Fig. 13   Mean unsigned error shown as a function of IEEP use and stimulus duration

Figure 14 shows the 3-way interaction of IEEP use with stimulus duration and sound source azimuth, $F(35, 3683) = 1.54$, $p < 0.022$, appears to be the result of larger errors in the rear hemisphere for the 250-ms stimuli, the increase in these errors due to IEEP use, and for some larger errors at 135° and 175° for unoccluded ears (the no-IEEP condition). Humans are normally vulnerable to front-back confusions; it is interesting that use of the IEEP seems to reduce the occurrence of these errors for the 4000-ms stimuli. It may be that the participants were moving their head to balance the level arriving at each ear, and thus derived some benefit from their use.
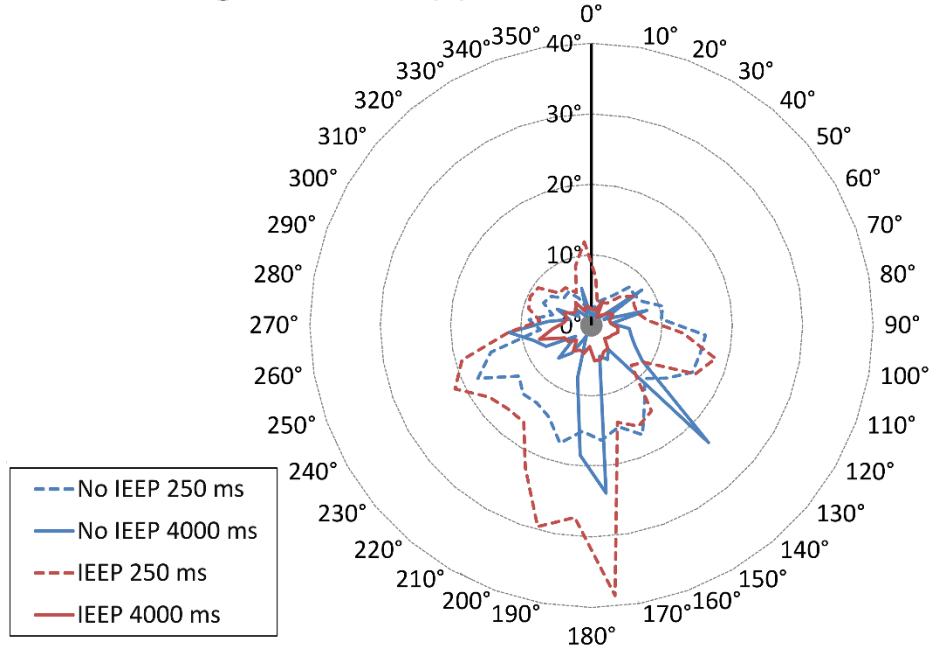
Fig. 14   Mean unsigned error shown as a function of IEEP use, stimulus duration, and sound source azimuth

3.6 Reversals

The primary spatial auditory concern for users of TCAPS devices is whether the device will increase front-back confusions significantly. Localization blur usually results in a slight increase in the average magnitude of errors. However, visual feedback will allow the listener to refine the auditory estimate if the target is within the listener's field of view. Conversely, front-back confusions, also known as reversals, can cause very large errors if the sound source azimuth is near 0° or 180°. Therefore, the data were coded for responses that were most likely due to reversals so that we could determine the degree to which reversals are the source of localization error.

For each trial, the error was compared to what the error would have been if the sound source had been in the reverse hemisphere. If $T < 180°$, the reversal T_r was computed as follows:

$$T_r = 180° - T, \tag{1}$$

else:

$$T_r = 540° - T. \tag{2}$$

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The error for this reversed azimuth angle was computed by subtracting it from the estimated angle

$$E_r = E - T_r. \tag{3}$$

A trial was coded as a reversal if the unsigned error was greater than 30° and if the unsigned error for the reversed azimuth angle was smaller than the unsigned error for the sound source azimuth. Reversals for sounds originating from near 0° or 180° are large. Conversely, if a sound originated from near 90° or 270°, it is difficult to determine whether an error is due to a front-back error or to localization blur. In practice, the effect is the same. Therefore, we include the limit that the original error must be greater than 30° for the trial to be coded as a reversal. Thus if

$$|E_r| < |E| \ \& \ |E| \geq 30° \stackrel{\text{def}}{=} \text{"reversal".} \tag{4}$$

Overall, only 83 of a total 4260 trials (1.9%) were coded as a reversal. Yet, most of the significant effects reported in the previous section are the result of a higher percentage of reversals for certain factor values. For instance, in Fig. 15 we see that more reversals occurred near the horizontal azimuths of 105°, 185°, and 245°. This effect is predicted near 180°. It should be noted that the increases near 105° and 245° might be an artifact of how we defined reversals. If we change the criterion for reversal to a minimum error of 20° or 45°, a slightly different pattern would emerge.
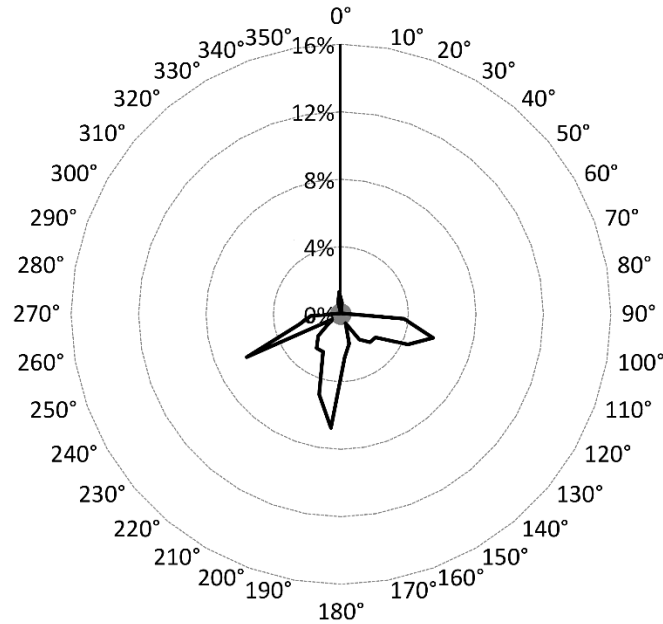
Percent Reversals

Fig. 15   Percent reversals shown as a function of sound source azimuth

More reversals were observed for the short-duration stimuli, especially when using the IEEP (Fig. 16). Although reversals occurred for only a small percentage of trials, it is clear that they are the source of differences in error between the no-IEEP and IEEP conditions for the 250-ms stimuli. For the short-duration stimuli (250 ms), IEEP use increased the percentage of reversals from 1.5% to 3.8%. For the long-duration trials, there were no reversals observed for the IEEP trials, but 1.4% of the no-IEEP trials were coded as reversals. Figure 17 shows the percent reversals as a function of IEEP use, stimulus duration, and sound source azimuth.

It is not clear why participants derived no significant benefit from the longer-duration stimuli for the ears unoccluded (no IEEP) condition. No feedback was given during training or testing. It may have been that the participants were overly confident in their ability to localize accurately when presented with the longer stimuli and made less of an effort to check their percept. Given feedback, participants might have adapted to the feedback and performed better for the ears unoccluded (no IEEP) condition.
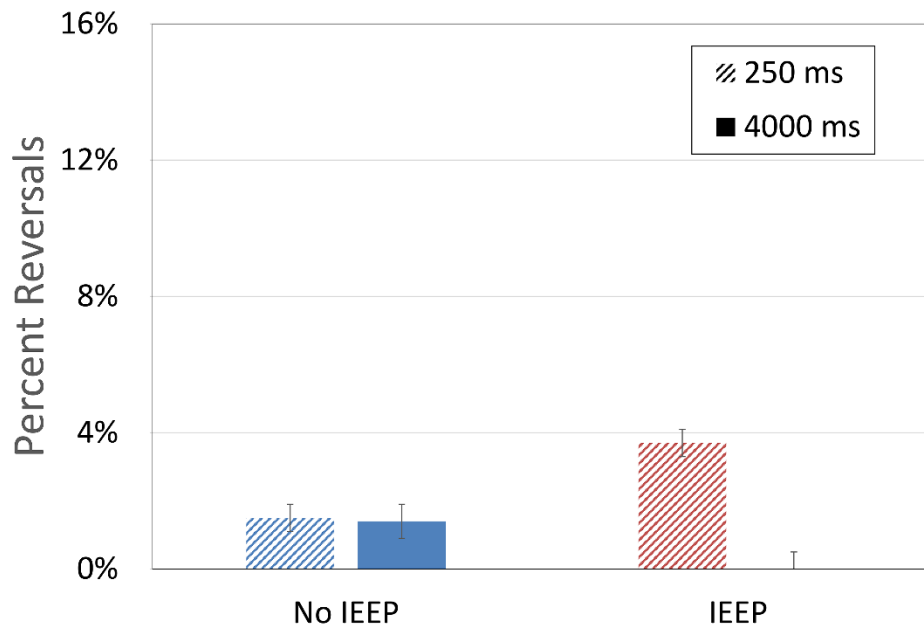

Fig. 16   Percent reversals observed as a function of stimulus duration and IEEP use
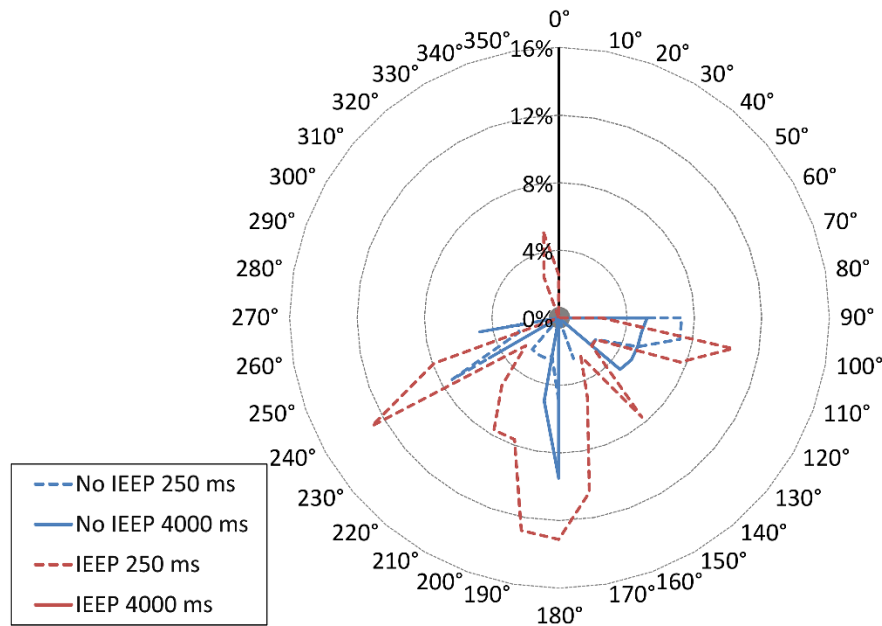
23

Percent Reversals

Fig. 17   Percent reversals as a function of IEEP use, stimulus duration, and sound source azimuth

4. Conclusion

Auditory localization ability was assessed for participants wearing the IEEP, a prototype TCAPS that also provides eye protection. Testing was conducted using one of the methods recently proposed by the DOD HCoE for an auditory localization measurement standard. All participant-wise performance was reported in comparison to performance with their ears unoccluded.

Listeners using the IEEP showed good localization accuracy with the device. The IEEP, after taking into account the known effects of sound source azimuth and stimulus duration, did not significantly change overall localization ability. However, it did have a small, but significant effect on accuracy for the short-duration (250-ms) stimuli, increasing the average unsigned error from 10.3° to 12.5°. This may be of particular relevance to Soldiers, as one sound that they might wish to localize is weapon fire, which is a short-duration sound. This is presumed to be due to the alteration of monaural cues caused by the insertion of the earphone tips as well as the fact that the short duration restricts the listener's ability to use movement cues to localize. Conversely, given the time to move one's head when responding to a longer stimulus (4000 ms), IEEP use decreased average unsigned error from 5.8° to 3.6°, perhaps because listeners learned to rotate until the input coming into both ears was equal.

The data were coded to determine the proportion of trials for which reversals had occurred. For the short-duration stimuli (250 ms), IEEP use increased the percentage of reversals from 1.5% to 3.8%. For long-duration stimuli (4000 ms), no reversals were observed for the IEEP condition.

Auditory localization ability is one of several factors to be considered when determining the quality of auditory situation awareness provided by a TCAPS device (Clasing and Casali 2014). Other factors include one's ability to detect, recognize, and identify sounds, including face-to-face and radio communications. Further acoustic testing is needed to ensure that hearing protection requirements are met. However, from the standpoint of auditory localization as tested in the current study, the IEEP has a minimal impact on localization performance, allowing the user to retain the majority of his or her auditory spatial capabilities.

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List of Symbols, Abbreviations, and Acronyms

ARA	Applied Research Associates, Inc.
dBA	A-weighted decibels
dB HL	Decibels relative to hearing level
dB SPL	Decibels relative to absolute sound pressure level
DOD	Department of Defense
HCoE	Hearing Center of Excellence
HPD	hearing protection device
IEEP	integrated eye and ear protection
MAA	Minimum Discriminable Audible Angle
NSRDEC	Natick Soldier Research, Development and Engineering Center
TCAPS	tactical communications and protection systems

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